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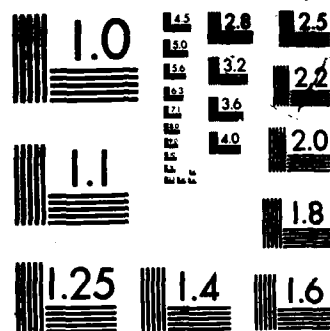
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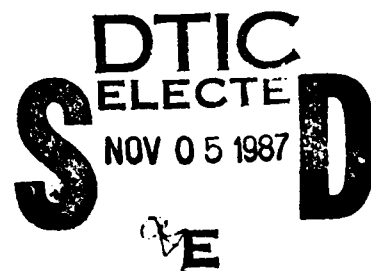
## Modulation of an Intense Beam by an External Microwave Source — Theory and Simulation

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## Modulation of an Intense Beam by an External Microwave Source—Theory and Simulation

The experimental demonstration<sup>1</sup> of deep current modulation in an intense relativistic electron beam ( $\sim 5$  kA, 500 keV) by a moderate external rf source ( $\sim 50$  kW) suggests strong potentials<sup>2,3</sup> to amplify rf power to gigawatts at frequencies between 1 GHz to 10 GHz. Several unusual properties were discovered in the experiments<sup>1,4</sup>, namely, the high degree of phase and amplitude stability in the output signal<sup>1</sup>, the ease with which the current modulation can be achieved and may be manipulated by the introduction of additional, undriven cavities downstream, and the possible avoidance of electrical breakdown at the gaps even at a high level of beam modulation<sup>5</sup>. These unexpected features are only partially understood. The major obstacle to a complete understanding is the highly nonlinear interaction in complex geometries involving the kinetic energy, rf energy, and the potential energy of the beam, all of which are of the same order of magnitude. The crucial role played by the potential energy, which necessarily accompanies an intense beam, renders the classical picture of beam bunching invalid.

We, therefore, resort to a time dependent, two-dimensional, fully electromagnetic particle code, CONDOR<sup>6</sup>, to simulate the response of an intense beam to an external rf excitation. This amplifier configuration has never been subject to particle simulation, although self-excited oscillations have been studied in the past<sup>7</sup>. We found that when the external rf drive is low, the induced rf current agrees well with the small signal theory<sup>1,7</sup>. Addition of a second cavity in the drift region significantly enhances the current modulation, without loss of phase stability, as observed in earlier experiments<sup>1</sup>. An analytical model is presented to show that the DC space charges associated with the intense beam may encourage current bunching as the beam traverses a modulating gap.

The harmonic content is assessed. The details, together with experimental observations, will be published elsewhere<sup>4</sup>.

To mimic the experiments as closely as possible, the simulation geometry [Fig. 1] consists of a 500 keV, annular IREB with beam radius  $r_b = 1.9$  cm and beam current  $I_0 = 5$  kA propagating along a metal cylinder of radius  $r_w = 2.4$  cm. A static 10 kG axial magnetic field confines the IREB. A gap feeding a coaxial cavity 5.6 cm long is inserted into the drift tube. An infinite radial transmission line (not shown) is attached to the outer wall of this cavity and "pumps" rf energy into the cavity at a frequency  $f = 1.37$  GHz, the resonance frequency of the cavity. At  $t = 0$ , the rf drive is turned on. At  $t = 6$  ns, after the fundamental mode of the cavity has saturated, the beam current is ramped up, reaching its full value at  $t = 11$  ns (5 ns rise). The simulation continues until  $t = 20$  ns.

For rf drives yielding gap voltages with amplitude  $V_1 = 30$  kV and  $V_1 = 6$  kV, the axial distribution of the normalized rf current  $I_1(z)/I_0$  in steady state is shown in Fig. 2. The temporal evolution of the beam current at a distance  $z = 28$  cm from the gap center is shown in Fig. 3a for the  $V_1 = 30$  keV case.

The above results may be compared with linear theory<sup>7,1</sup>: An rf voltage  $V_1 \sin \omega t$  at the gap would induce an rf current  $I_1(z) \cos(\omega(t - z/v_0))$  at a position  $z$  downstream, where

$$I_1(z) \approx I_0 \bar{V} \sin \bar{z} \quad (1)$$

Here,  $v_0$  is the average electron speed in the drift region<sup>8</sup>,  $\bar{V} = (eV_1/m_0 c^2) \delta / (\gamma_0^2 \beta_0 \alpha^{1/2})$ ,  $\bar{z} = 2\pi(z/\lambda) \alpha^{1/2} / \beta_0^2 \gamma_0$ ,  $\delta = \beta_0^2 / (\beta_0^2 - \alpha)$ ,  $\alpha = I_0 / I_S \gamma_0^3 \beta_0$ ,  $I_S = 8.53 \text{ kA} / \ln(r_w/r_b)$ ,  $\lambda = 2\pi c / \omega$ ,  $\beta_0 = v_0 / c$ ,  $\gamma_0 = (1 - \beta_0^2)^{-1/2}$ . The axial dependence  $I_1(z)/I_0$  according to expression (1) is shown by the dashed curves in Fig. 2, using the same parameters as in the simulation:  $I_0 = 5 \text{ kA}$ ,  $\lambda = 21.9 \text{ cm}$ ,  $I_S = 36.5 \text{ kA}$ ,  $\gamma_0 = 1.67$ . Note that Eq. (1) and Fig. 2

imply linear dependence of  $I_1$  on  $V_1$  when  $V_1$  is small. As  $V_1$  increases, the current modulation would contain harmonic components  $I_n(z) \approx 2 I_0 J_n(n \sqrt{V} \sin \bar{z})$  where  $J_n$  is the Bessel function of order  $n$ . This estimate shows that only the fundamental component ( $n=1$ ) is significant if  $\sqrt{V} \leq 0.3$ .

To obtain a current modulation comparable to  $I_0$ ,  $V_1$  should also be of the same order of the beam voltage. It is impractical to excite such a large gap voltage directly from an external rf source. Instead, one may insert a second cavity downstream [Fig. 1b], at a location where the current modulation (by the first cavity) reaches a maximum<sup>1</sup>. This second cavity is identical to the first, but is not externally driven. Using the same rf drive as that for Fig. 3a, we show in Fig. 3b the temporal evolution of the beam current at 6 cm downstream from the second gap, at which the gap voltage is 330 keV. The total current modulation there increases to 57%, including all harmonics. In fact, the modulation level continues to increase over the remaining 10 cm of propagation distance, reaching 85%. No particle reflections were observed at the second gap, nor transients were important. These results compare favorably to both the experimental two-cavity result, in which the cavity separation was 5 cm and modulation greater than 80% was observed at 1.328 GHz<sup>1</sup>, and to more recent results in which the separation is 32 cm<sup>4</sup>. In this situation, the harmonic content is considerable, with as many as eleven harmonics clearly observable in the current measured immediately downstream from the second gap.

Substantial current modulation immediately beyond a gap is a property of an intense beam which cannot be expected from the conventional klystron theory. While the details are not fully understood, the following scenario emerges<sup>5</sup>: When the beam current  $I_0$  approaches the limiting value,  $I_L$ , the

DC potential energy is nontrivial, especially near the gap. If the modulating voltage  $V_1$  at the gap is sufficiently large, the instantaneous beam current may exceed the limiting value during the part of the rf cycle when the rf voltage is in the same phase as the retarding voltage caused by the DC self field of the beam. This then leads to strong current modulation once the beam exits the gap. In a simple model, the current modulation  $I_1/I_0$  at the gap exit reads:

$$\left(I_1/I_0\right)_{\text{exit}} = \left(\frac{2}{\pi}\right) \left(1 - v_{\text{th}}^2/V_1^2\right)^{1/2} \quad (2)$$

where the threshold voltage  $V_{\text{th}}$  is given by

$$V_{\text{th}} = \frac{m_0 c^2}{|e|} \left\{ \gamma_{\text{inj}} - \left[ 1 + \left( \frac{I_0}{I_L} \right)^{2/3} \left( \gamma_{\text{inj}}^{2/3} - 1 \right) \right]^{3/2} \right\} \quad (3)$$

in terms of the injection  $\gamma$  and the limiting current  $I_L$ . This current modulation is absent if  $V_1 < V_{\text{th}}$ , but rises rapidly once  $V_1 > V_{\text{th}}$ , and becomes insensitive to  $V_1$  if the latter substantially exceeds  $V_{\text{th}}$  [c.f. Eq. (2)]. These features are also reflected qualitatively in experiments.

Finally, by varying the phase of the external rf drive in the two-cavity geometry [Fig. 1b], we have found that the current modulation signal is phase-locked to the external drive to within an error of  $1.1 \pm .6\%$ , in agreement with the experimental observation<sup>1</sup>.

In summary, several unusual features observed in experiments on the modulation of an intense beam are confirmed in the particle simulation. Useful analytic models are constructed.

We are grateful to M. Friedman and V. Serlin for many stimulating discussions, and for their support. We are also indebted to Scott Brandon and to Adam Drobot for their assistance in applying CONDOR<sup>6</sup> to this problem. This work is supported by the Department of Energy, Contract No. DE-AI05-86 ER 13585.



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6. CONDOR is an extension of the MASK particle code, discussed in A. Palevsky and A. Drobot, "Application of E-M P.I.C. codes to microwave devices," in Proc. 9th Conf. Numerical Simulation of Plasmas (Northwestern Univ., Evanston, IL), July 1980 (unpublished).
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8. Since the electrons already spend some energy to set up the space charge depression in the drift region, their drift speed  $v_0$  is somewhat less than the value at injection.

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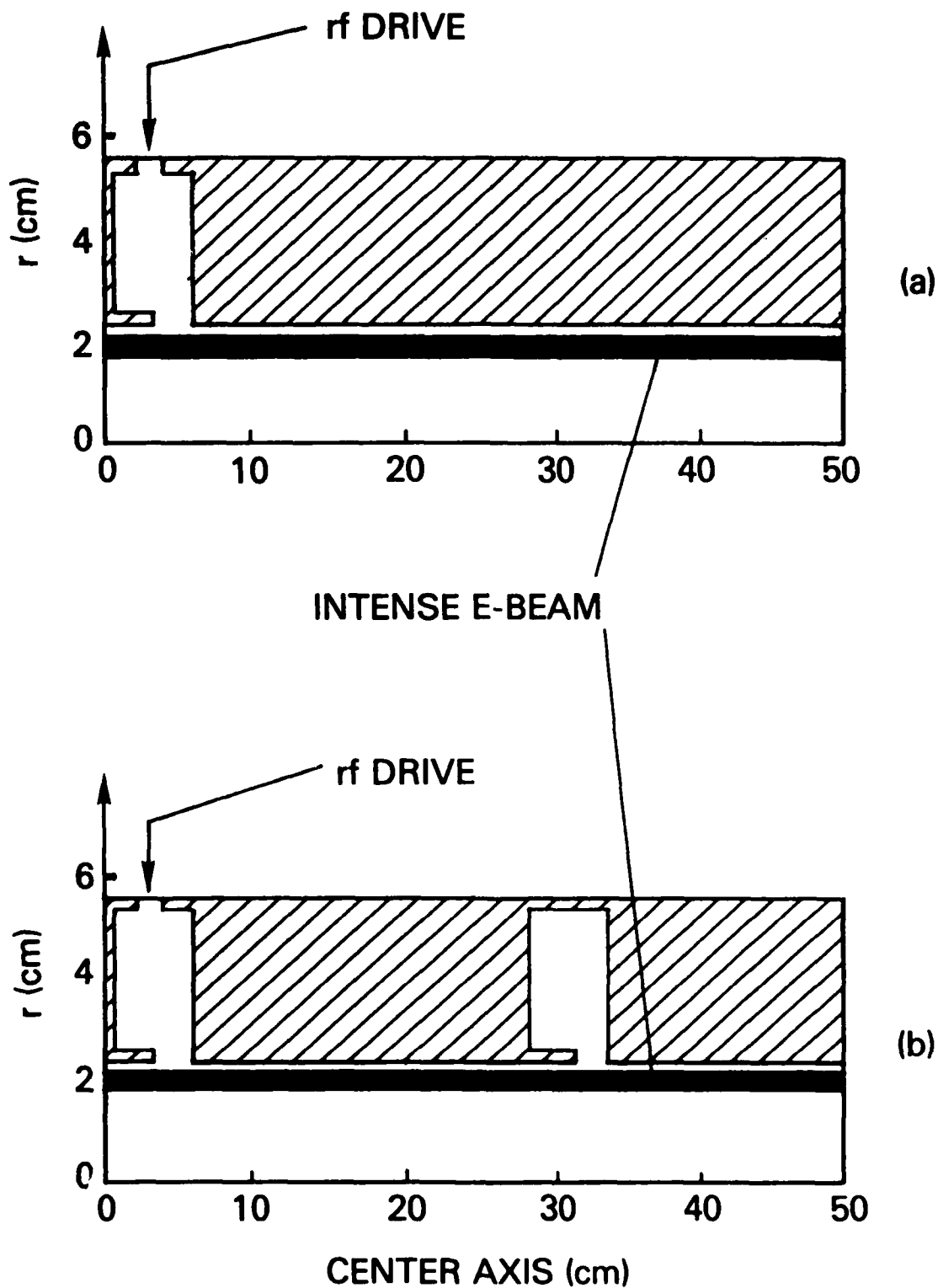


Fig. 1 (a) The geometry. Current modulation is provided by the externally driven cavity at left.  
 (b) A second cavity is inserted to enhance current modulation.

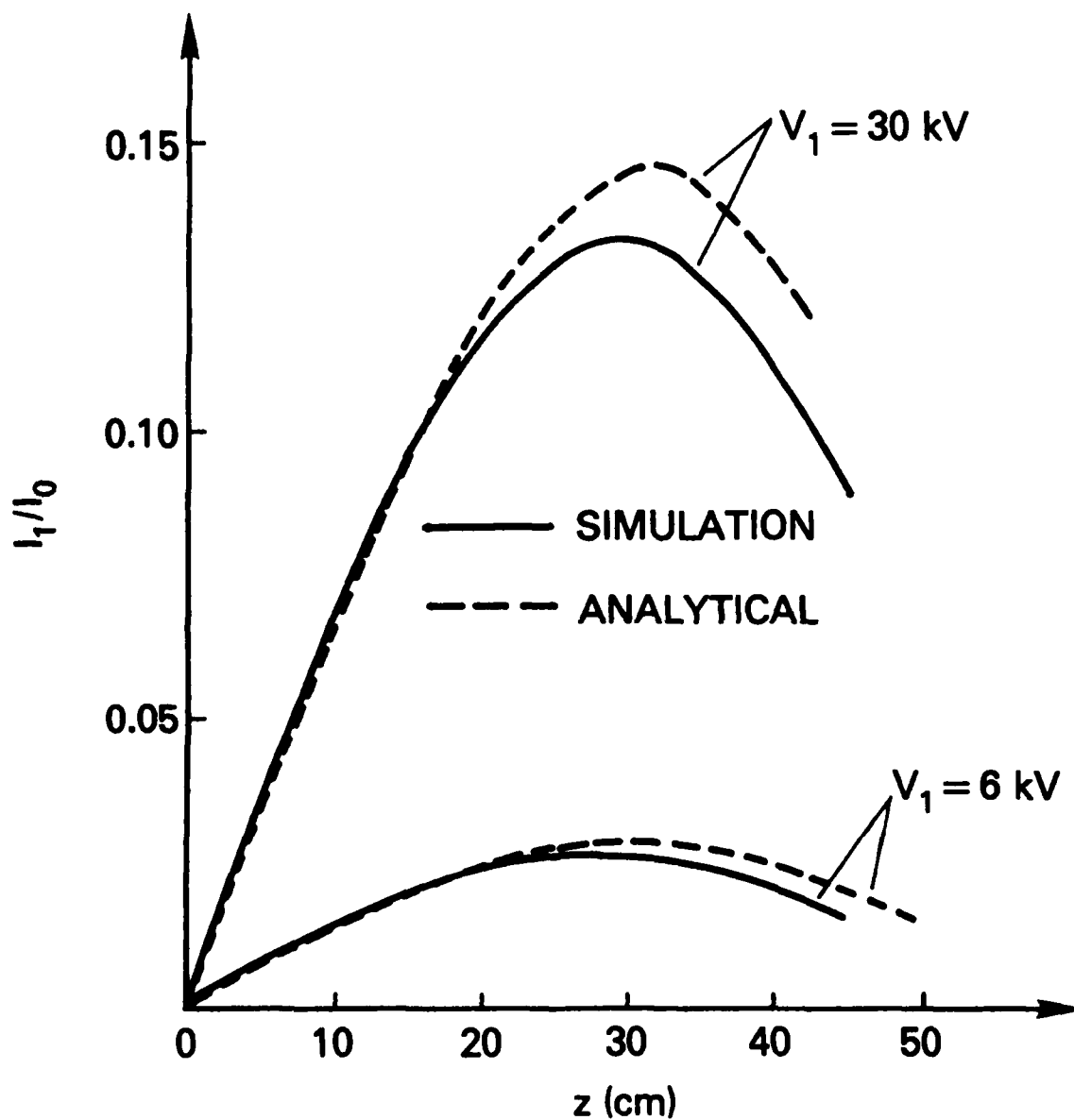


Fig. 2

Fraction of the modulated current for Fig. 1a, at two levels of the rf drive.

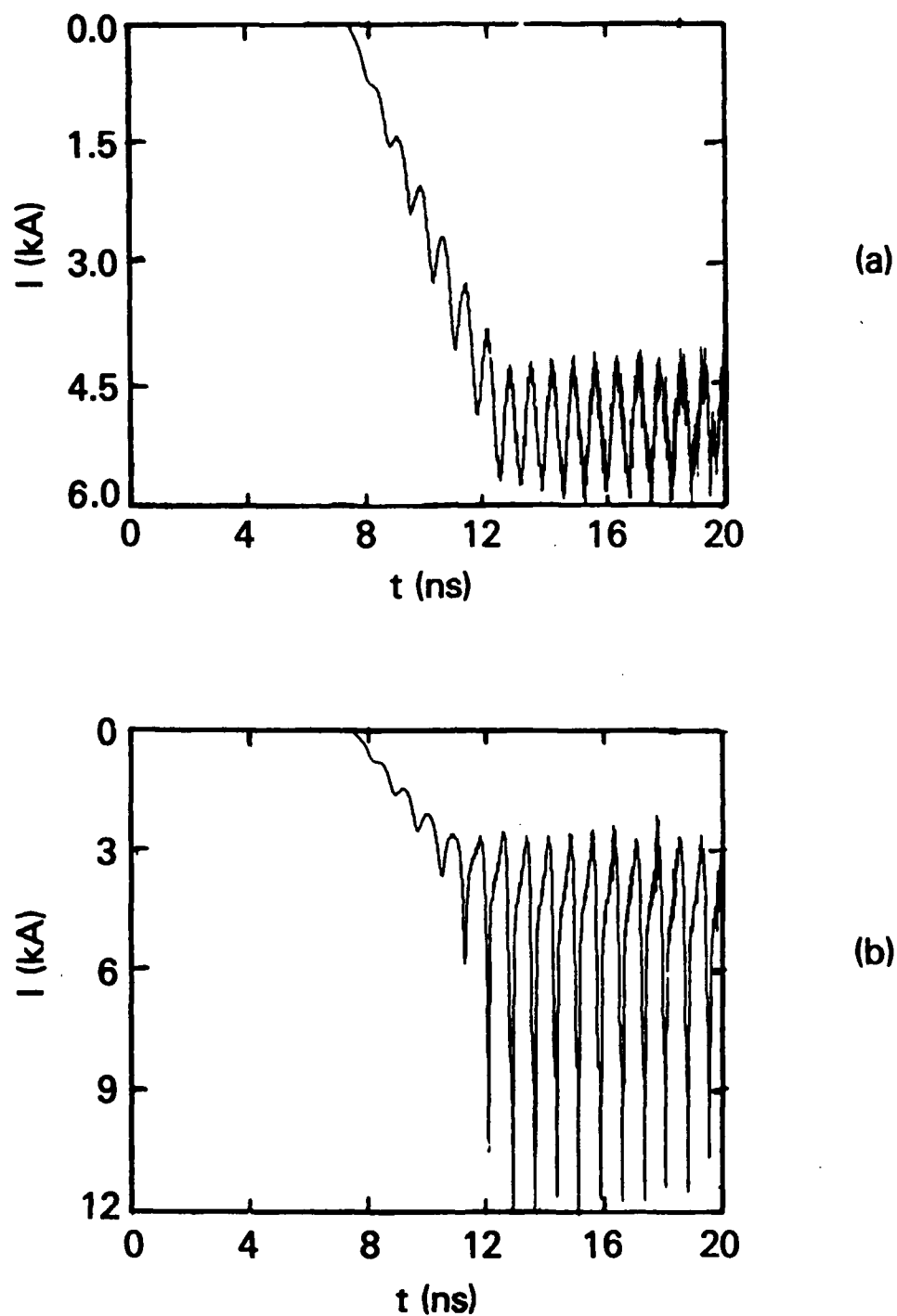


Fig. 3 (a) Current response measured at  $z = 28$  cm from the gap for Fig. 1a, with gap voltage  $V_1 = 30$  kV.

(b) Current response measured at 6 cm downstream of the second (right) cavity in Fig. 1b, with  $V_1 = 30$  kV at the first cavity.

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